A Highly Miniaturized μPPT Thruster for Attitude Orbit Control

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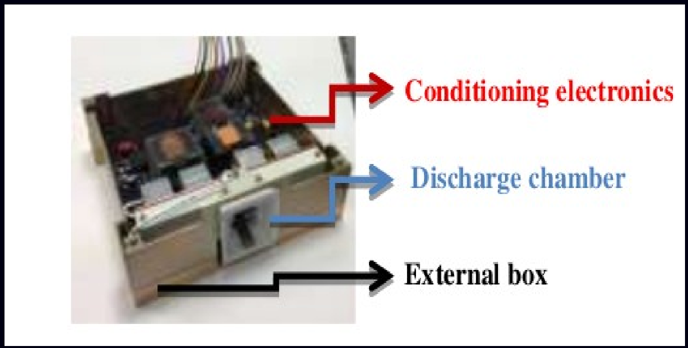
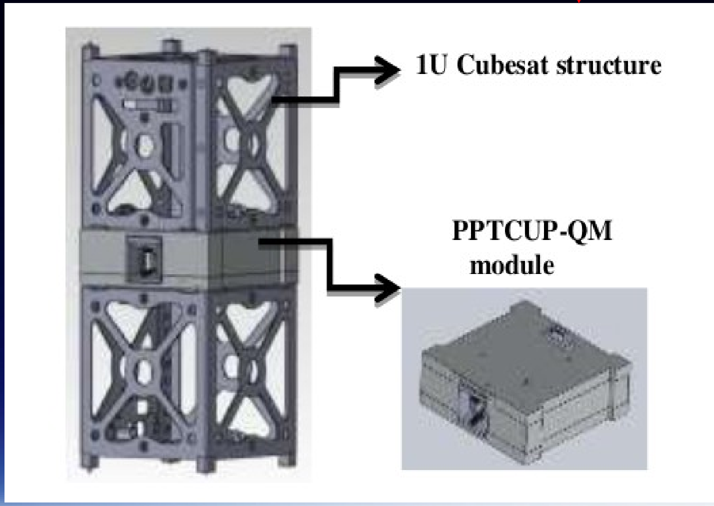
Presentation Outline

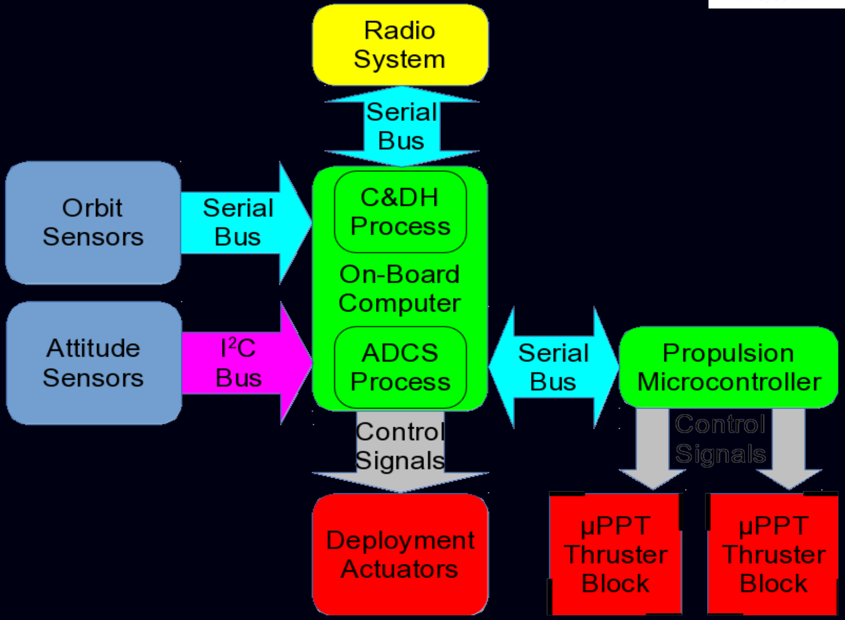
1. PPTCUP Development and Nanosatellite
2. PPTCUP Model
3. PPTCUP Testing Results
4. PPTCUP Orbit Keeping and Formation Control Simulation Results
5. Conclusions

1. Pulsed Plasma Thruster and Nanosatellite

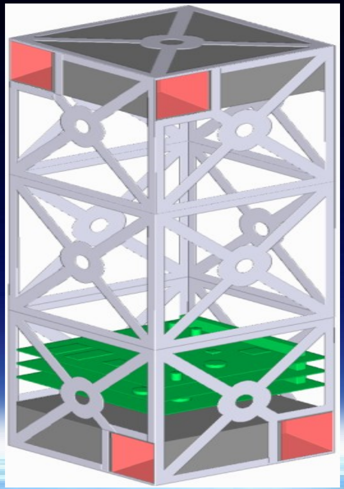


Current
PPT/Nanosatellite





Future
PPT/Nanosatllite



2. Pulsed Plasma Thruster Model

a. Modified Nozzle Inductance of PPTCUP

$$L' = 0.6 + 0.4 \ln \frac{h}{w + l}$$

h: distance between electrode; l: length of electrodes;
w: width of electrodes

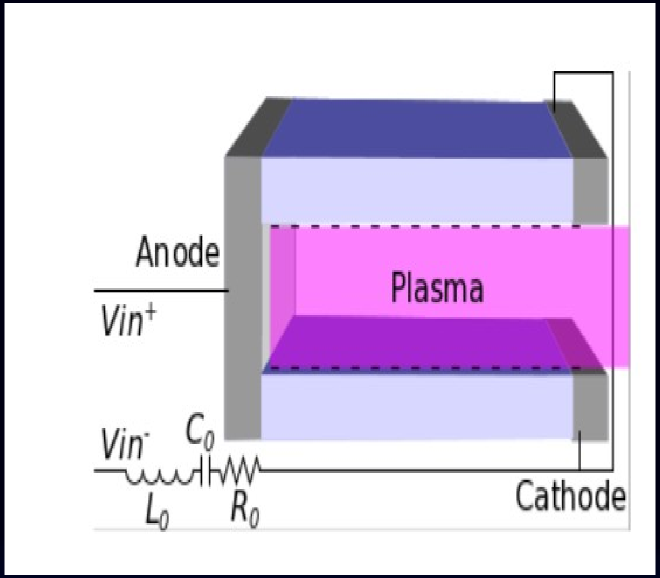
b. Motion of the Plasma Bulk

$$T = m\dot{x} + \dot{m}\ddot{x} = T_l + T_g$$

T: total force; m: mass of the current sheet;
F: pulse frequency;i: total current;u0 the magnetic permeability

$$T_L = F \frac{\mu_0}{2} \frac{h}{w} \int_0^t i^2 dt$$

Lorentz Force



Gas Dynamic Expansion

$$T_g = \dot{m} \left[\frac{(1 + \frac{r-1}{2})^{\frac{-r}{r-1}} + r(\frac{2}{r+1})^{\frac{r}{r-1}}}{\mathrm{r}(\frac{2}{r+1})^{\frac{r+1}{2(\mathrm{r}-1)}}} \sqrt{rRT_e} \right]$$

Te: plasma electron temperature; R: molar gas constant; r
Ratio of specific heats,r=1.3 for Teflon

2. Pulsed Plasma Thruster Model

c. Circuit Equations of PPT

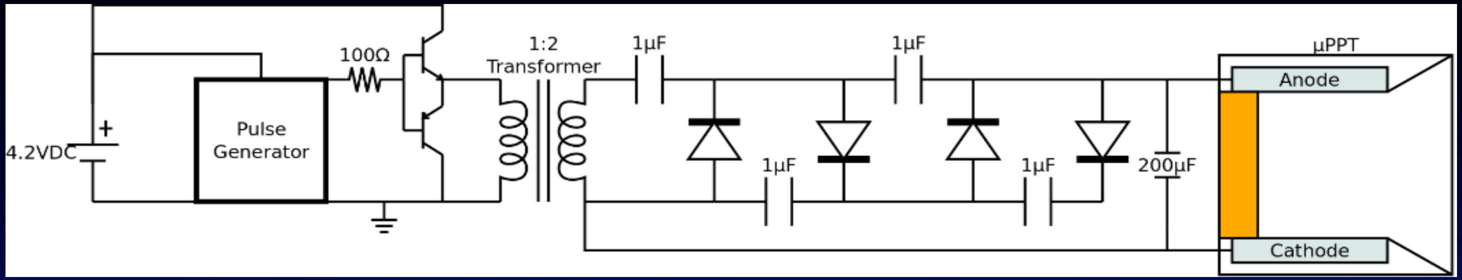
$$V_0 - \frac{1}{C}\int_0^t i\,dt = i(\mathrm{R}_c + \mathrm{R}_e + \mathrm{R}_{pe} + \mathrm{R}_p) + (\mathrm{L}_c + \mathrm{L}_e + \mu_0 \frac{h}{w}\mathrm{x} + \mu_0 \frac{h\delta}{2w}\mathrm{x})\dot{\mathrm{i}} + \mu_0 \frac{h}{w}\dot{\mathrm{x}}\mathrm{i}$$

$$\dot{m} = \frac{i^2 \mu_0 A}{w^2 V_{crt} 4.404}$$

$$R_p = 8.08 \frac{h}{T_e^{\frac{3}{4}} w}\sqrt{\frac{\mu_0}{\tau} \ln 1.24X10^7 \left(\frac{T_e^3}{n_e}\right)^{1/2}}$$

$$m = \frac{\mu_0 h}{w V_{crt} 4.404}\int_0^t i^2 dt$$

V0: initial voltage; c: capacitance of capacitor; Rc.Re.Rpe.Rp: resistance of capacitor, wires and leads, plate electrodes and plasma; Lc.Le: inductance of capacitor, wires and leads; ne: electron density; \tau: characteristic pulse time; \xi: current sheet thickness
F: pulse frequency;i: total current;u0 the magnetic permeability



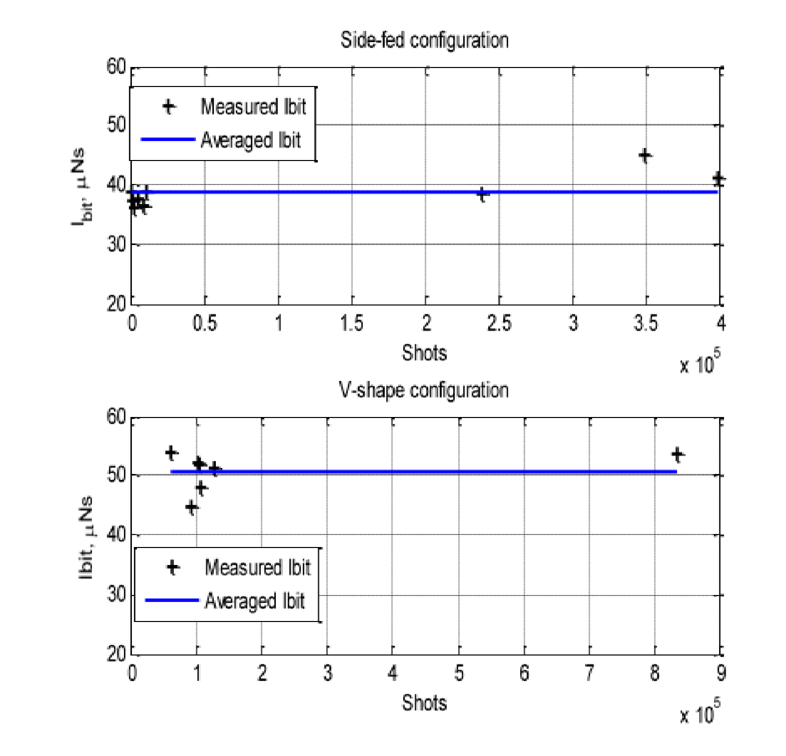
d. Impulse Bit of PPT

$$I_{bit} = \int (T_l + T_g)\,\mathrm{dt} + \mathrm{m}_n V_{dec}$$

Mn: mass of neutral gases mixture; Vdec: velocity of decomposed material

3.Pulsed Plasma Thruster Testing Results

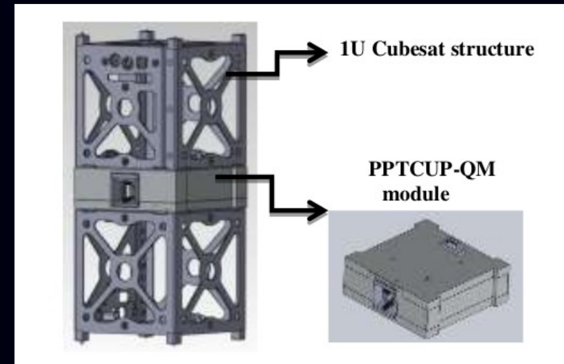
d. Impulse Bit of PPT



Parameter	Post thermal test	Post mechanical test	PPTCUP-EM [5]
Ibit (μNs)	39.2 ± 3.5	40.0 ± 3.5	38.2 ± 3.4
m_{bit} (μg)	6.5 ± 0.1	5.9 ± 0.1	6.4 ± 0.1
Isp (s)	613 ± 54	696 ± 62	608 ± 55
η_{th} (%)	5.9 ± 0.7	6.8 ± 0.9	5.7 ± 0.7

Vibration Test and Vacuum Chamber used for Performances Test (Mars Space Ltd/IAC14-C.4.10)

4. Simulation Results



- Case 1: PPTCUP Orbit Keeping

a. Life Time;

b. Change in orbit semi major axis per revolution

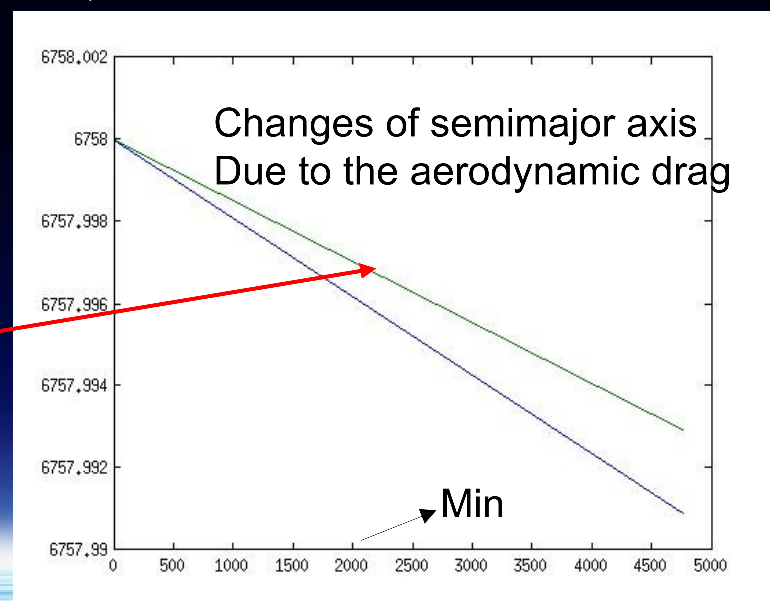
$$L = \frac{-A_h}{\Delta a}$$

$$\Delta a = -2\pi \frac{C_d A}{m} \rho a^2$$

L: Life Time; Ah: Atmospheric scale height; a semi major axis
Cd: drag coefficient; A: satellite cross sectional area;
m: satellite mass

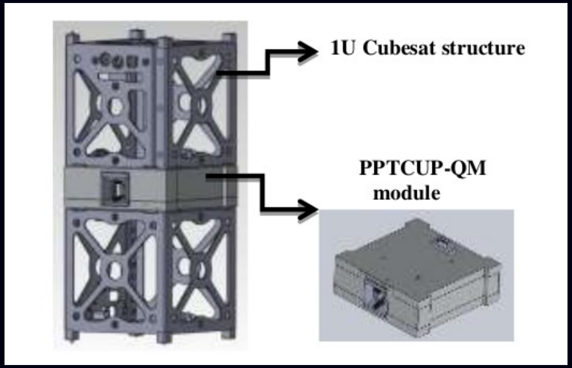
c. Non-singular Equinoctial Orbit elements (NSEOE) instead of the classical orbital elecments (COE)

$$\frac{da}{dt} = \frac{2a^2}{nab}\left[\ P_2 \sin L - P_1 \cos L\ \ a_r + g a_\theta \right]$$



4. Simulation Results

- Case 1: PPTCUP Orbit Keeping



Altitude	Size	Natural Life	Life with PPT	Increase Life
250km	1u 2u 3u	5.7d 11d 17d	17d 22d 28d	200% 100% 66%
350km	1u 2u 3u	2m 8d 4m 16d 6m 24d	5m 21d 8m 10m 8d	150% 75% 50%
450km	1u 2u 3u	1y 5m 2y 10m 4y 2m	3y 3m 4y 8m 6y	133% 67% 44%

4. Simulation Results

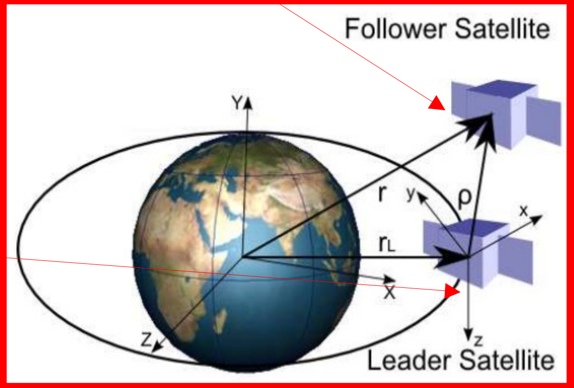
- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing
- Modelling: Hill Clohessy and Wiltshire Equations, considering Relative J_2 effects between the leader satellite and the follower satellite (or the mothership and the servicing satellite); U=Control, D=J_2.

$$\begin{aligned}
\ddot{x} - 2\dot{\theta}\dot{y} - \left(\dot{\theta}^2 x + \ddot{\theta} y\right) + \mu\left(\frac{r_L + x}{r_F^3} - \frac{1}{r_L^2}\right) &= \frac{1}{m_F}U_x + \frac{1}{m_F}D_x \\
\ddot{y} + 2\dot{\theta}\dot{x} + \left(\ddot{\theta} x - \dot{\theta}^2 y\right) + \frac{\mu}{r_F^3} y &= \frac{1}{m_F}U_y + \frac{1}{m_F}D_y \\
\ddot{z} + \frac{\mu}{r_F^3} z &= \frac{1}{m_F}U_z + \frac{1}{m_F}D_z
\end{aligned}$$

Follower/Servicing satellite

$$\begin{aligned}
\ddot{r}_L - r_L\dot{\theta}^2 + \frac{\mu}{r_L^2} &= 0 \\
r_L\ddot{\theta} + 2\dot{\theta}\dot{r}_L &= 0
\end{aligned}$$

Leader/Mothership



4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Satellite Orbit and PPT Parameters

Mass of Satellite 4kg
Formation Size 1km Circular Projected Formation
Formation Initial Errors: 10m, 10 m, 10m
Mass of PPT 180g mass+90g electrics
Dimensions 90.17mmx95.89mmx31mm
Total Impulse 42Ns
Specific Impulse 608s
Power 0.3-4w
Thrust to Power ratio 20uN/w
Impulse Bit 40uNs
Altitude 350 km
Electricity 0 degree
Inclination 0 degree

4. Simulation Results

PPT controller design: Asymptotic Second-order Sliding Mode Control (2nd SMC)

$$\dot{X}(t) = \begin{bmatrix} X_2(t) \\ f(X) \end{bmatrix} + \begin{bmatrix} O_{n\times n} \\ g(X) \end{bmatrix} (u(t) + D(t))$$

$$\ddot{X}(t) = A(X)\dot{X}(t) + B(\dot{u}(t) + \dot{D}(t))$$

$$A(X) = \begin{bmatrix} O_{3\times 3} & I_3 \\ \frac{\partial}{\partial x_1} f(X) & \frac{\partial}{\partial X_2} f(X) \end{bmatrix} = \begin{bmatrix} O_{n\times n} & I_n \\ a_1(X) & a_2(X) \end{bmatrix}$$

$$B = \begin{bmatrix} O_{3\times 3} \\ g \end{bmatrix}.$$

Sliding plane

$$\sigma(t) = Ce(t) = \begin{bmatrix} M & I_3 \end{bmatrix} e(t) = Me_1(t) + e_2(t)$$

Proposed 2nd SMC

$$v(t) = -k_1\sigma(t) - k_2 \int_0^t \mathrm{sgn}(\sigma(t))dt$$

$$\Sigma(t) = \begin{bmatrix} \sigma(t) \\ \dot{\sigma}(t) \end{bmatrix}$$

- Build Lyapunov functions

$$V_e(t) = \frac{1}{2} e_1^T(t) M^{-1} e_1(t)$$

$$\sigma(t) = \dot{\sigma}(t) = 0$$

$$\dot{V}$$

$$V_\sigma(t) = \frac{1}{2}\Sigma^T(t) \begin{bmatrix} I_3 & \varepsilon_1 I_3 \\ \varepsilon_1 I_3 & \varepsilon_2 I_3 \end{bmatrix} \Sigma(t) + \sum_{i=1}^{3} G_i |\sigma_i(t)|$$

Locally Asymptotically Stable

4. Simulation Results

PPT controller design: Asymptotic Second-order Sliding Mode Control (2nd SMC)

$$\dot{X}(t) = \begin{bmatrix} X_2(t) \\ f(X) \end{bmatrix} + \begin{bmatrix} O_{n\times n} \\ g(X) \end{bmatrix} (u(t) + D(t))$$

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$$B = \begin{bmatrix} O_{3\times 3} \\ g \end{bmatrix}.$$

- **Sliding plane**

$$\sigma(t) = Ce(t) = \begin{bmatrix} M & I_3 \end{bmatrix} e(t) = Me_1(t) + e_2(t)$$

- **Proposed 2nd SMC**

$$v(t) = -k_1\sigma(t) - k_2 \int_0^t \mathrm{sgn}(\sigma(t))dt$$

$$\Sigma(t) = \begin{bmatrix} \sigma(t) \\ \dot{\sigma}(t) \end{bmatrix}$$

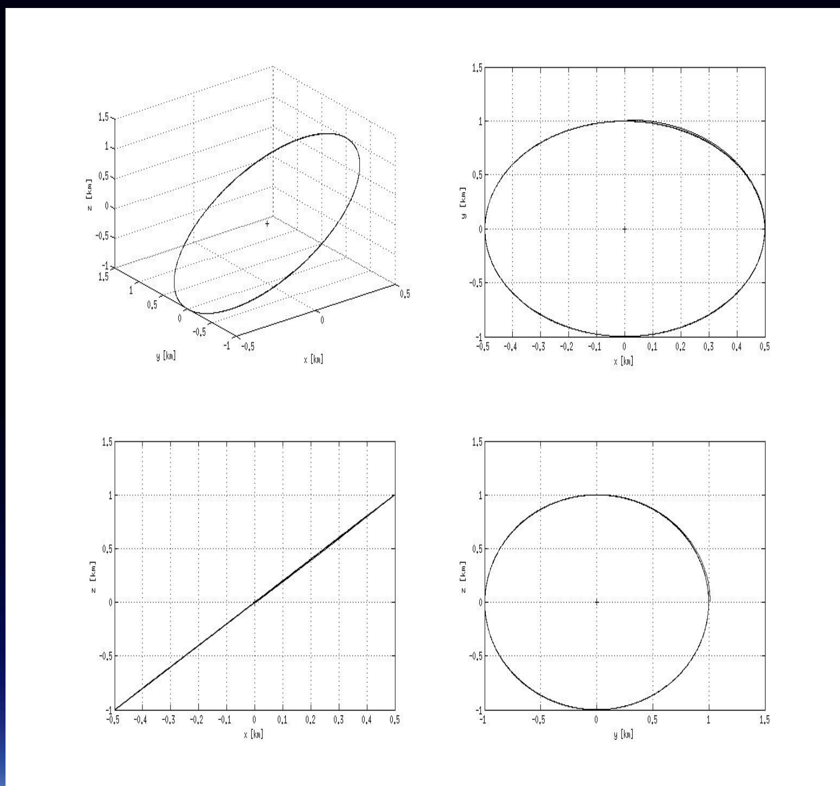
- PPT Modulator Output is calculated as:

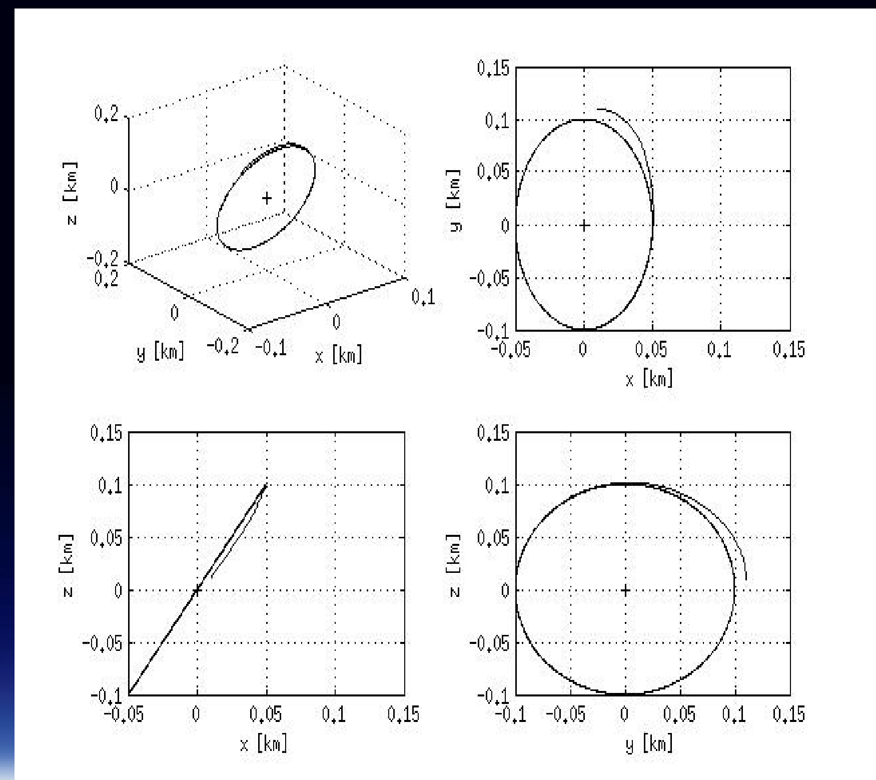
$$p_i(t_k) = \begin{cases} \triangle U_M sgn(\triangle U_i(t_k)) & if \left|\triangle U_i(t_k) \geq \triangle U_M\right| \\ 0 & if \left|\triangle U_i(t_k) \leq \triangle U_M\right| \end{cases}$$

4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Formation Shape/Size 1 km	Formation Shape/Size 0.1 km

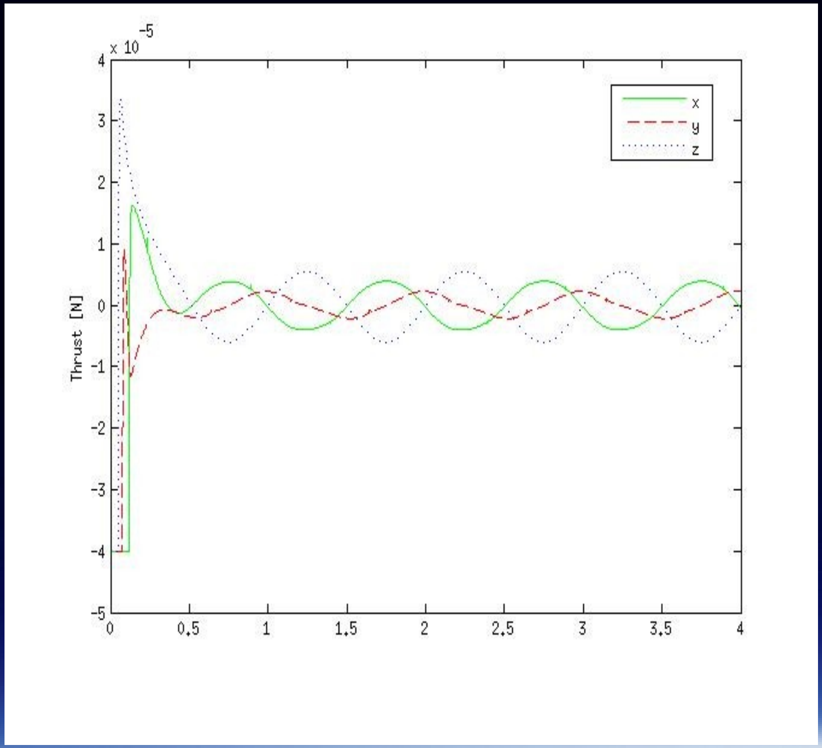




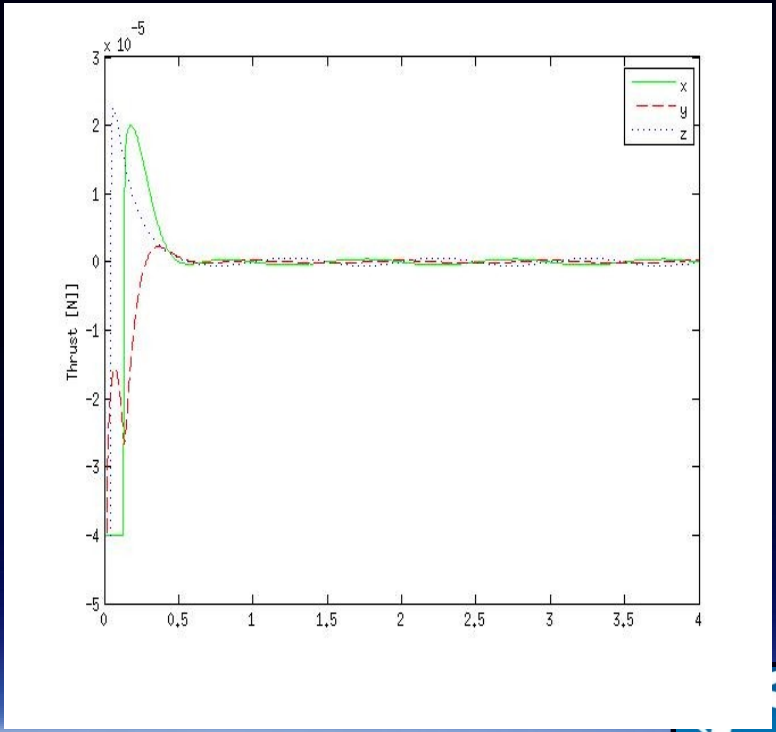
4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Formation Size 1 km Control Input



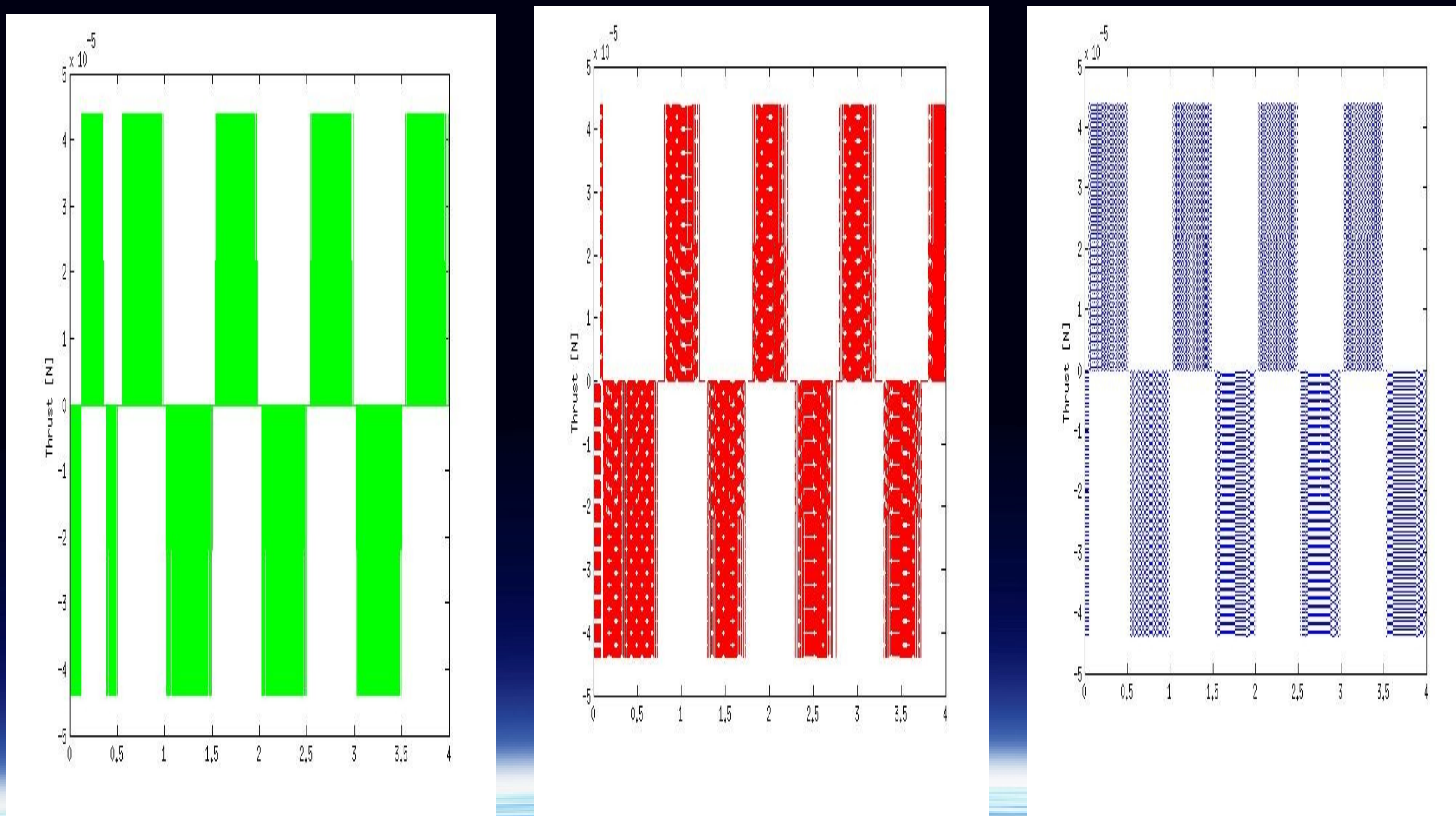
Formation Size 0.1 km Control Input



4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

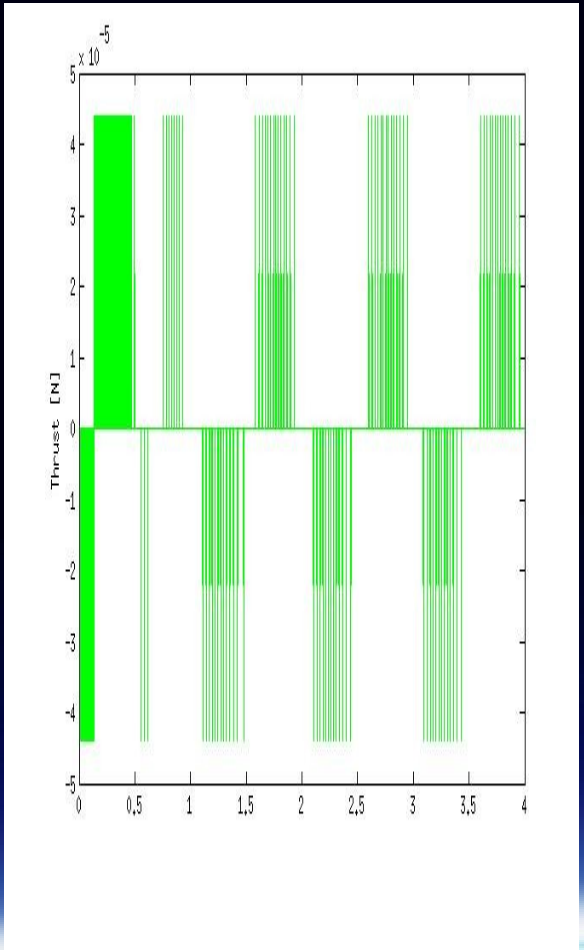
Formation Size 1 km PPT Impulse Profile

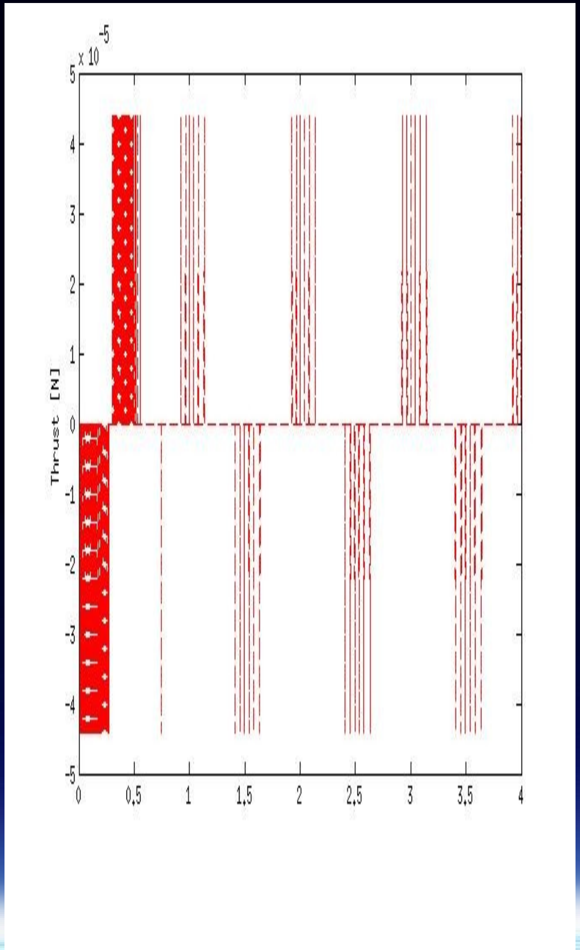


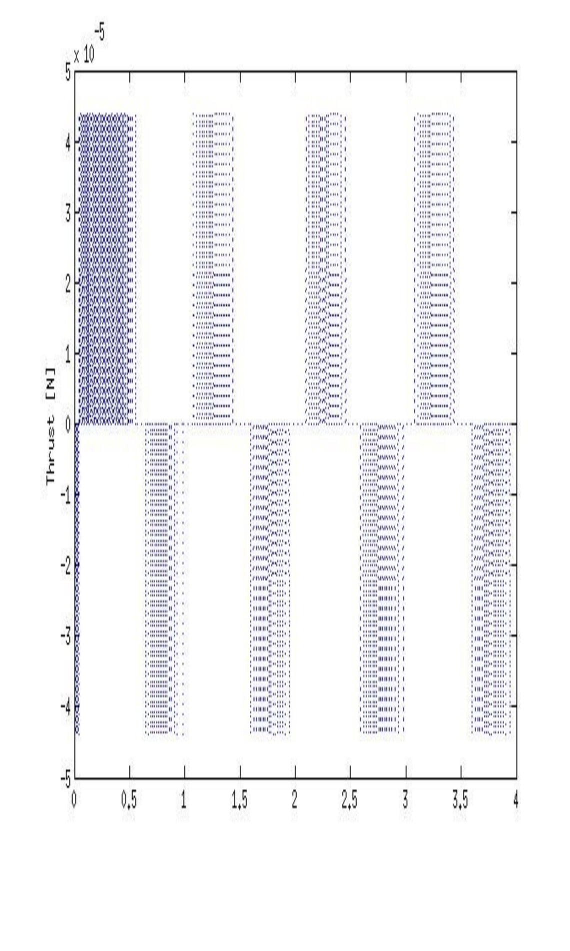
4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Formation Size 0.1 km PPT Impulse Profile in 4 orbits





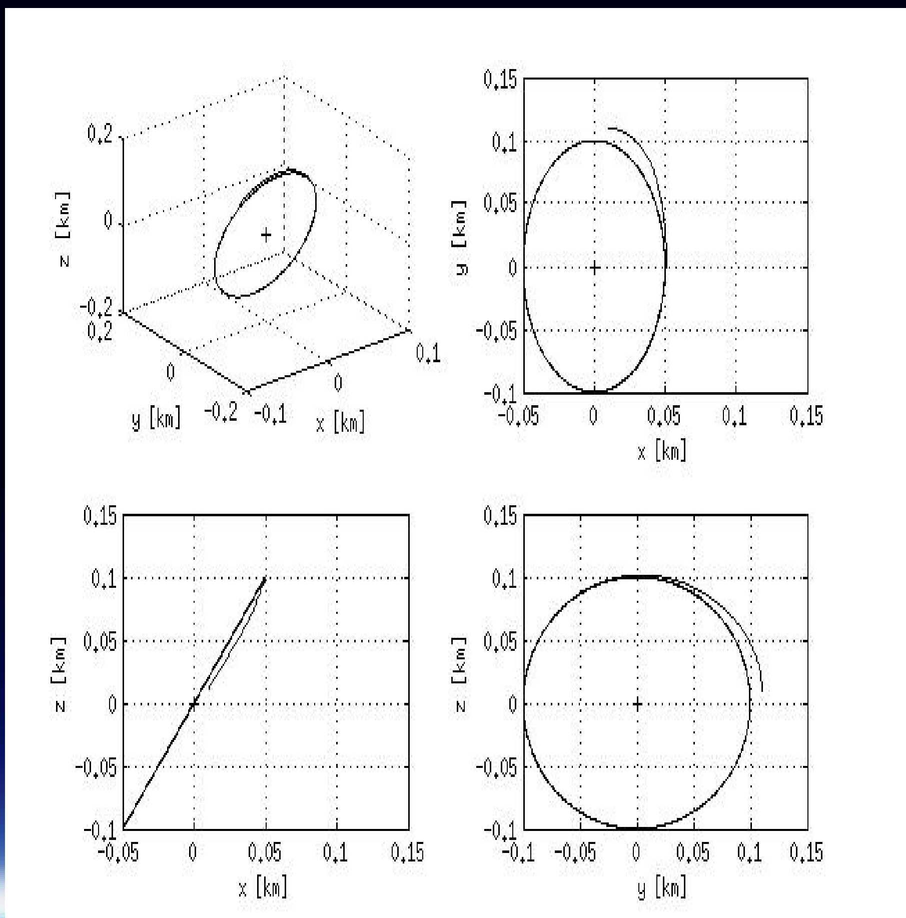


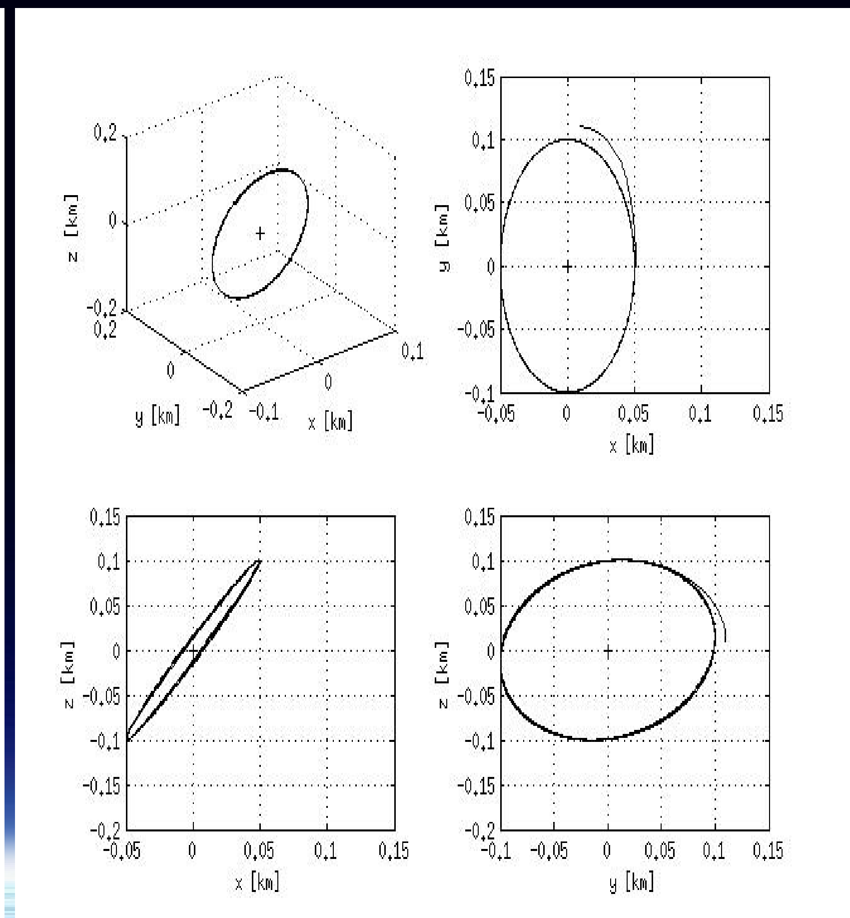
4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Formation Shape/Size 0.1 km

Using XYZ Thruster	Using X and Y thrusters only

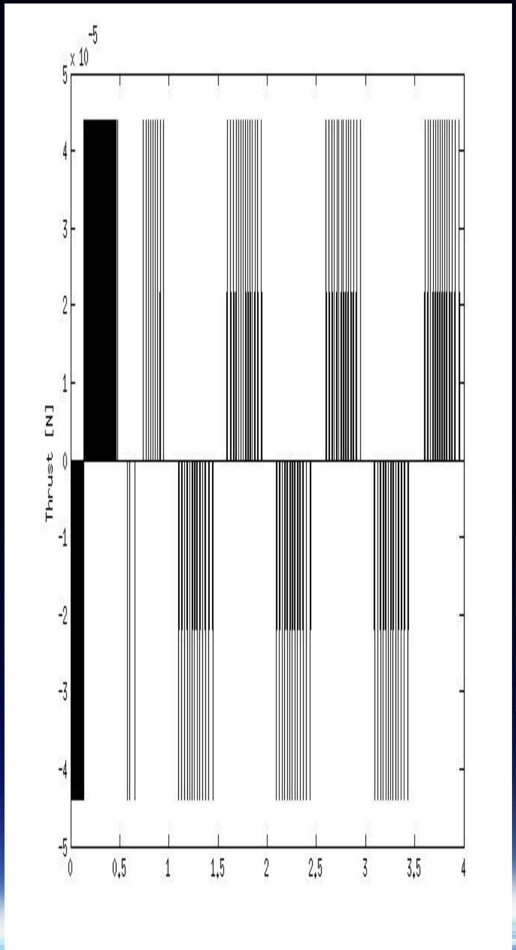


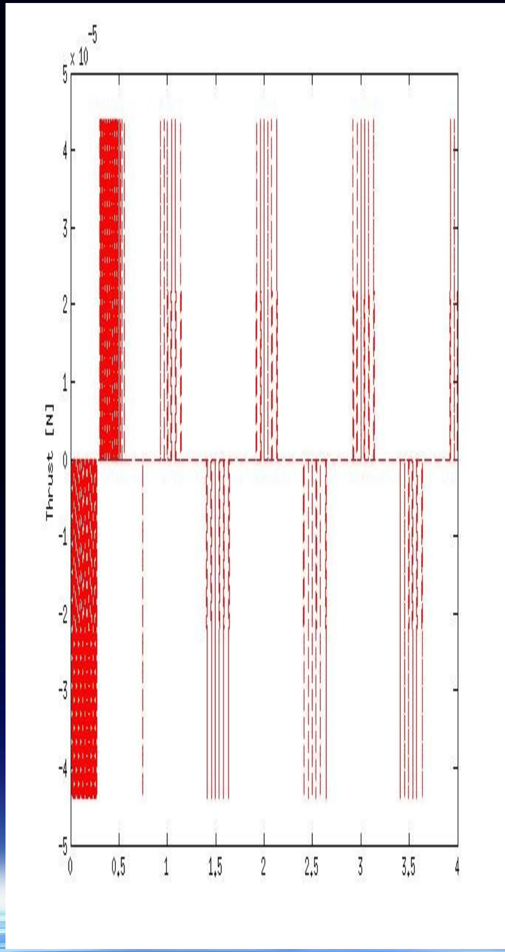


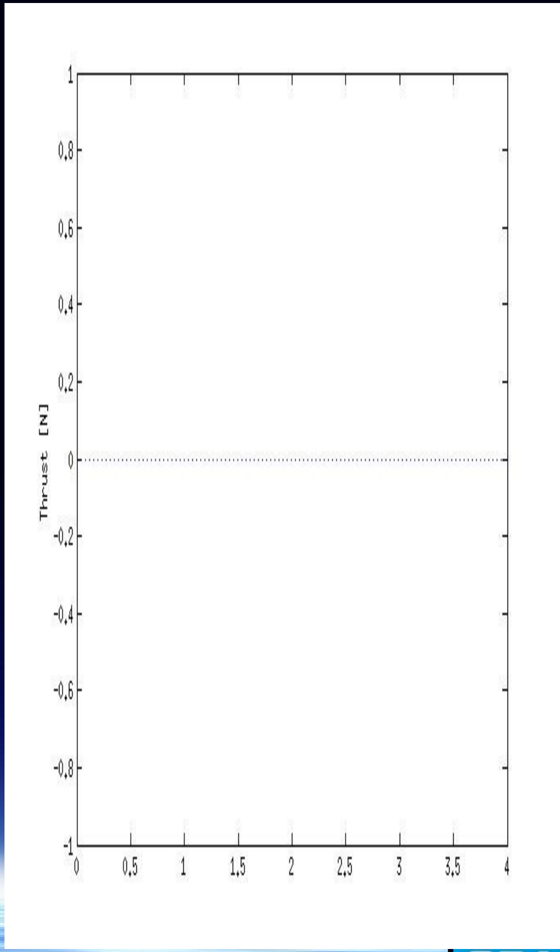
4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing Thruster/Time

Formation Size 0.1 km PPT Impulse Profile X and Y Thruster Only





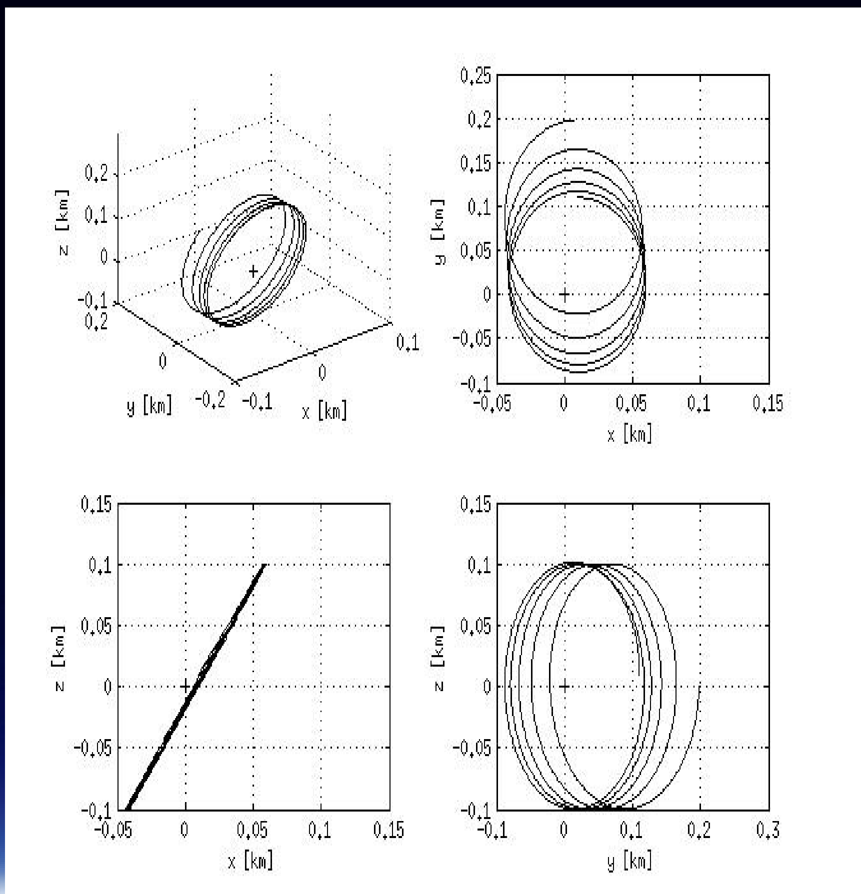


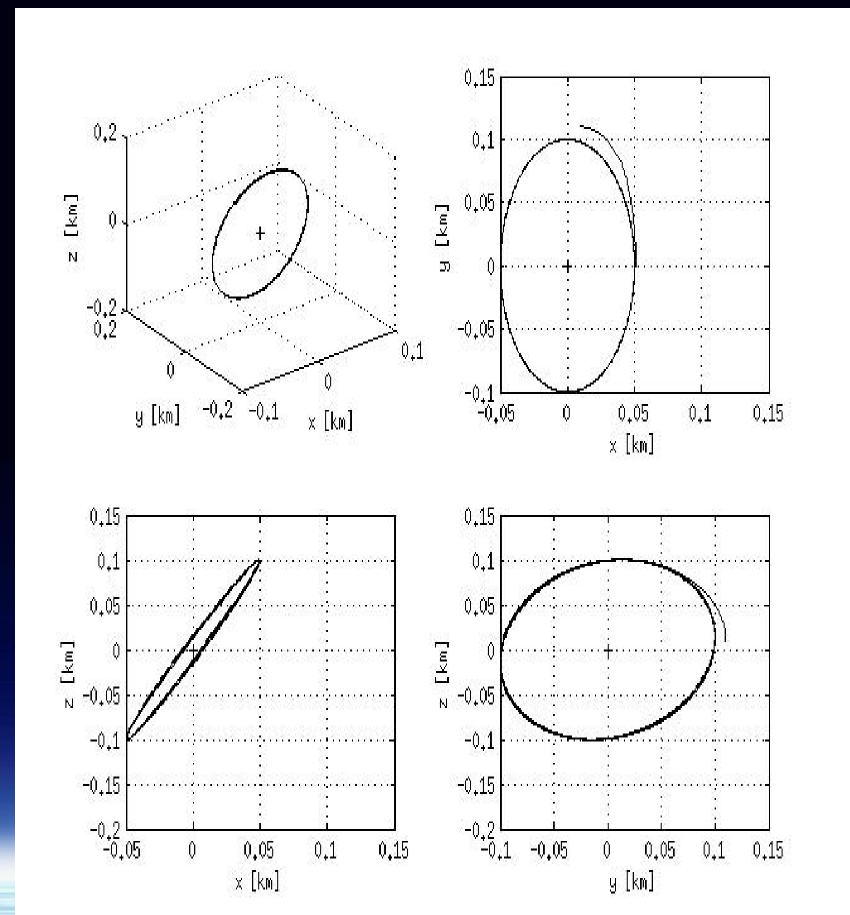
4. Simulation Results

- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

Formation Shape/Size 0.1 km

Using X and Z Thrusters only	Using X and Y thrusters only

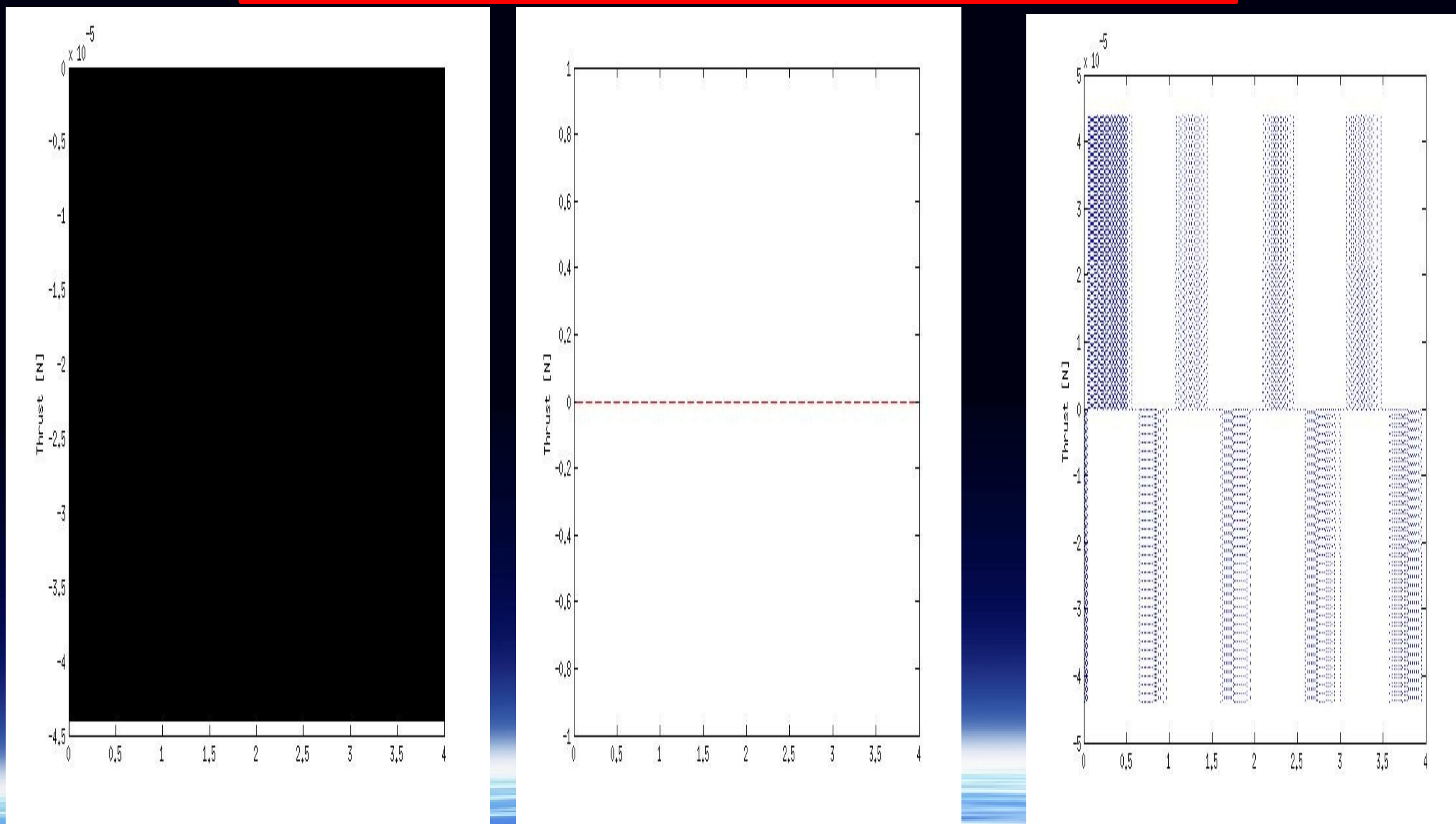




4. Simulation Results

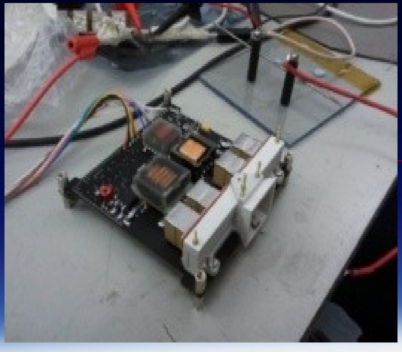
- Case 2 PPT Formation Flying/rendezvous/docking/In orbit Servicing

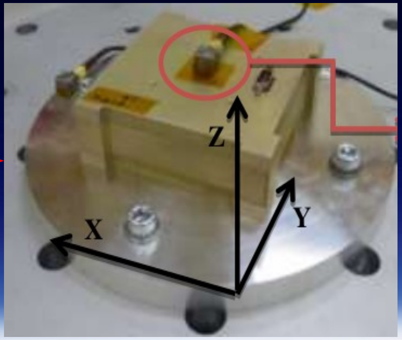
Formation Size 0.1 km PPT Impulse Profile
X and Z Thruster only

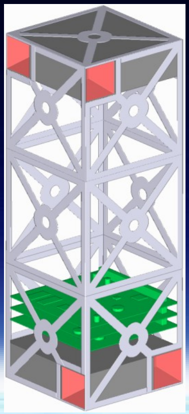


Conclusions

1. Miniaturization of PPTCUP and Nanosatellite by Clyde Space, Mars Space and the University of Southampton, final qualification testing.
2. PPTCUP can provide 40uN-80uN thrust pulse 1 million times in succession.
3. PPTCUP testing results and simulation results show that PPTCUP is capable for nanosatellite missions.
4. Future works: Numerical Optimization using mathematical model and new configurations of PPTCUP for precise attitude control.







Thank You for Listening!